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STUDY OF INSERTION DEVICES EFFECTS IN SIRIUS

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Abstract

SIRIUS is the 4th generation synchrotron light source built and operated by the Brazilian Synchrotron Light Laboratory (LNLS). SIRIUS is currently operating with six beamlines and eight others are at different stages of deployment [1]. In this work we report on the development of simulation tools to analyze the impact of insertion devices (IDs) on SIRIUS beam orbit, optics and dynamic aperture (DA), aiming at defining their specifications for external suppliers and verifying the feasibility of installing existing IDs. In particular, we analyze the fields of two IDS used in the previous LNLS synchrotron light source (UVX), now decommissioned: one planar 2T hybrid wiggler and one EPU of the type Apple-II. These IDs were installed in SIRIUS in 2022 and are now temporarily serving as commissioning light sources for PAINEIRA and SABIÁ beamlines. Furthermore, we also analyze the effects of two new ID models that will be used as titular light sources for CARNAÚBA, CATERETÊ, EMA, and PAINEIRA beamlines. One is an In-Vaccum Undulator (IVU) and the other is a Vertically Polarizing Undulator (VPU). An undulator built in-house will be used as a temporary light source for the SAPUCAIA beamline commissioning and its effects on SIRIUS beam parameters are also reported.

INTRODUCTION

SIRIUS storage ring optic allows for the generation of remarkable X-ray brightness from insertion devices due to the machine low natural emittance of 0.25 nm rad and to the small values of betatron functions at the center of low-β straight sections, which are $\beta_x = 1.36$ m and $\beta_y = 1.60$ m. These focusing values produce a good matching between the phase spaces of electron and photon beams when considering 4-meter-long undulators as radiation sources, which reduces the effective phase space area of the photon beam [2]. To take advantage of the high-brightness light generated by IDs it is necessary to ensure that these devices will not degrade the electron beam parameters, especially the non-linear dynamics, which is more difficult to correct and could reduce the ring dynamic aperture, that might be prejudicial for top-up operation at SIRIUS.

SIRIUS Phase-I IDs

Currently SIRIUS storage ring has four different models of IDs installed, as detailed in Table 1. The APU devices are commissioning IDs and will be replaced by titular ones, except for the MANACÁ beamline [3] which will operate using two APU22s. SABIÁ and PAINEIRA are currently in the commissioning stage and are using two refurbished IDs from the first LNLS storage ring UVX. These two beamlines will have their light sources changed, SABIÁ will receive DELTA-type undulators [4] and PAINEIRA will have an IVU, whose parameters are presented in Table 2. Two VPUs are being acquired for CARNAÚBA and CATERETÊ beamlines. SAPUCAIA is in installation phase and will start its commissioning in the second semester with an undulator built in-house called PAPU50. The final ID of this beamline will be the other two of the commissioning APU22s.

Table 1: Comissioning IDs.

	EPU50	W180	APU22	APU58	PAPU50
β	Low	Low	Low High	Low	High
λ [mm]	50	180	22	58	50
B_0[T]	0.47	1.00	0.70	0.95	0.42
K_{max}	2.2	16.8	1.4	5.2	1.9
g_{min}[mm]	22.0	49.0	8.0	15.8	24
L [m]	2.7	2.3	1.1	1.0	0.9

Table 2: SIRIUS phase-I titular IDs.

	IVU18	VPU29	DELTA52	APU22
β	Low	Low	Low	High
λ [mm]	18.5	29	52.5	22
B_0[T]	1.22	0.80	1.25	0.70
K_{max}	2.1	2.2	6.1	1.4
g_{min}[mm]	4.3	9.7	13.6	8.0
L [m]	2.0	1.5	1.1	1.1

REFURBISHED IDS

Simulations

Radia [5] models calibrated with field measurements of each device were used to compute the 3D magnetic field generated by these IDs, then the Runge-Kutta method was applied to calculate their kick maps, which are shown in Figure 1. To calibrate the models, the remanent magnetization of the blocks was adjusted to provide the same field amplitude as the real devices, the block's widths and space between cassettes were also adjusted to give a similar field transverse profile with those from the real IDs. To run the beam dynamics simulations, Trackcpp [6] was used. The results showed that no coupling was introduced, as expected. Furthermore, the deviations in tunes and in the betatron func-

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tions (beta-beating r.m.s) due to intrinsic focusing effects are described in Table 3.

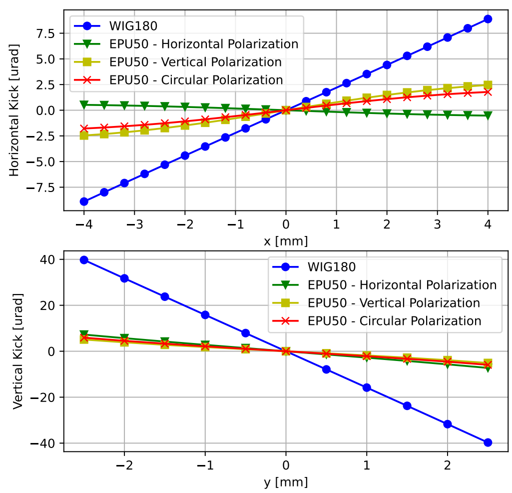

Figure 1: Kick maps for each ID configuration. The kicks dependence on transverse positions is approximately linear, indicating that these devices should not introduce harmful nonlinearities on the lattice.

The beta-beating introduced on the lattice model was corrected using local quadrupoles placed nearby the straight section of each ID, and the betatron tune shift correction was performed globally using two knobs, adjusting the focusing and defocusing of combined the quadrupoles families.

Table 3: Linear optics perturbations introduced by the refurbished IDs. Clearly, the larger perturbation was caused by the wiggler, as expected due to its strongest effective quadrupolar field.

ID. config	$\Delta\nu_x$ $\times1000$	$\Delta\nu_y$ $\times1000$	$\frac{\Delta\beta_x}{\beta_x}$ [%]	$\frac{\Delta\beta_y}{\beta_y}$ [%]
WIG180	-0.3	+2.1	0.14	0.65
EPU50 - Hor. Pol	+0.0	+0.4	0.01	0.12
EPU50 - Ver. Pol	-0.1	+0.3	0.05	0.08
EPU50 - Cir. Pol	-0.1	+0.3	0.04	0.09

After linear optics correction, calculations of DA and tune diffusion were performed, numerical analysis of fundamental frequencies (NAFF) [7] was used to calculate the diffusion map. The results are shown in Figure 2. It is seen that there is a small reduction in the DA from about $x = -11$ mm to $x = -10$ mm. However, the DA of the actual machine is already smaller than these values, thus the reduction observed is within the uncertainty limit of the simulations. Large diffusion is found only near the boundaries of the DA.

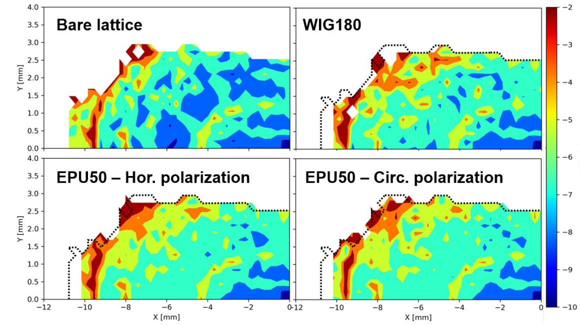

Figure 2: Impacts of the refurbished IDs on DA and in tunes diffusion. The traced line represents the DA boundary for the bare lattice. The configurations shown for EPU are the circular and horizontal polarizations. It is seen that their impact on DA are similar, as it is also the case for vertical polarization.

Measurements

After the installation of the IDs in the machine, linear optics from closed orbit (LOCO) [8] measurements were performed to estimate their effects on optics. In the case of the wiggler, the characterization and corrections were done considering the gap at its operational value, which is 49.73 mm. Without correction, the LOCO-calibrated model had a 2% beta-beating in both planes. The measured betatron coupling was 0.5% higher than the operation value of 1.0% but the injection efficiency was not affected. To correct the coupling to its operation value, first it was adjusted to 0% with skew quadrupoles and then increased to the reference value. Regarding the EPU, measurements and corrections were done considering horizontal polarization and gap 36.00 mm, which is the current operating configuration, fixed for now. The beta-beating found was less than 1% in both planes, and a coupling of 1.3% was measured, which was also corrected to 1.0% in the same way as for the wiggler.

NEW IDS

To simulate the impact of the incoming IDs and define their specifications for purchase with external manufacturers, it was necessary to construct their Radia models. Then the following steps after modeling were the same as for the refurbished IDs, that is, the kick maps (shown in Figure 3) were calculated and inserted into the SIRIUS lattice. It is important to mention that this modeling-simulation step was an iterative process, in view of the fact that the roll-off specs for the new IDs were based on the non-linear effects that this roll-off would cause in the electron beam dynamics.

The roll-off specification for VPU29 was established considering the field gradient in the vertical direction since this device works as a rotated planar undulator, whereas it has a horizontal field and opens its gap horizontally. The established acceptable value for its roll-off was 2% at $y = 3$ mm. With respect to IVU18, the roll-off specification was established to 0.02% at $x = 6$ mm.

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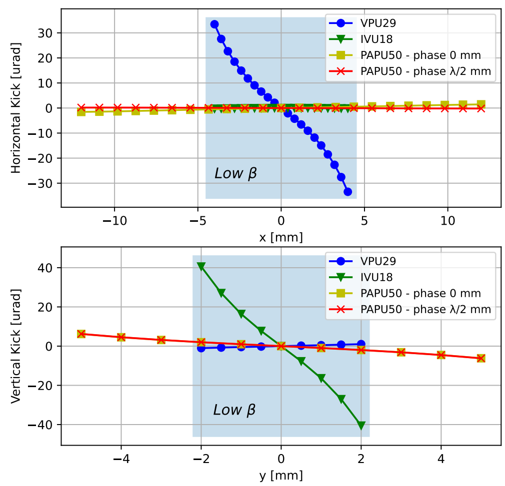

Figure 3: Kick maps for the new IDs. VPU29 and IVU18 have the highest multipolar terms. It is interesting to note that the intrinsic focusing effect happens in the horizontal direction for VPU, different from conventional IDs where the focusing happens in the vertical direction. Moreover, since PAPU50 will be inserted on a high-β straight section its kick maps had to be calculated on a larger region in the (x, y) plane.

The betatron tune shifts and the r.m.s of the beta-beating introduced by these IDs are presented in Table 4, where it is seen that the IVU is responsible for introducing the largest perturbations on linear optics. These nominal ID models do not introduce linear coupling.

Table 4: Linear optics perturbations introduced by the new IDs.

ID. config	$\Delta\nu_x$ ×1000	$\Delta\nu_y$ ×1000	$\frac{\Delta\beta_x}{\beta_x}$ [%]	$\frac{\Delta\beta_y}{\beta_y}$ [%]
VPU29	+0.7	-0.1	0.45	0.03
IVU18	+0.0	+2.0	0.00	0.80
PAPU50 ph. 0	-0.2	+0.3	0.13	0.14
PAPU50 ph. $\frac{\lambda}{2}$	-0.0	+0.3	0.02	0.14

The impacts in DA and in betatron tune diffusion are shown in Figure 4. It is verified that the DA does not experience a significant reduction with any of these IDs, however, the introduction of more diffusion is observed, especially for the case of IVU18 and PAPU50 with zero vertical field (phase $\lambda/2$ mm).

Effects on Equilibrium Parameters

The effects on beam emittance and energy spread with the inclusion of the IDs were estimated using analytical expressions based on the synchrotron radiation integrals [9]. Figure 5 shows that a reduction in horizontal beam emittance

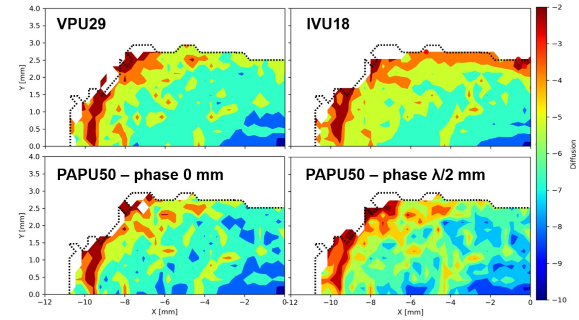

Figure 4: Dynamic aperture and tune diffusion after introducing the new IDs in SIRIUS lattice. The traced line represents the DA boundary for the bare lattice

is achieved by introducing IDs in the lattice, this behavior is also observed for the energy spread.

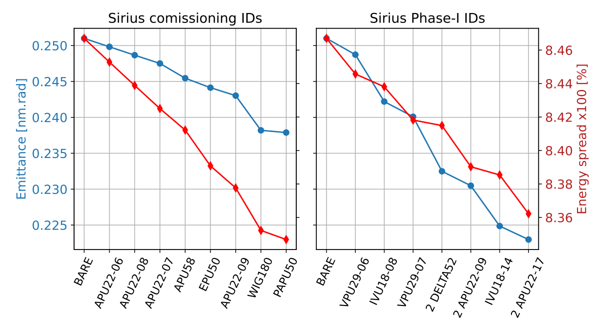

Figure 5: Cumulative effects of the IDs in the electron beam emittance and energy spread. A significant effect on energy spread is not observed, however for the case of Phase-I IDs, with was observed a decrease of 10% on beam emittance.

CONCLUSIONS

The results show that the introduction of the refurbished IDs on SIRIUS is acceptable to the beam dynamics, the linear effects can be easily corrected by adjusting the strengths of adjacent quadrupoles. However, further characterizations for different configurations of phase and gap for the EPU50 are still necessary. In the case of the new IDs, despite the fact that it is observed an increase in the tune diffusion, the DA is not significantly reduced. Furthermore, a 10% reduction in emittance is expected. The methods for correction of the perturbations introduced by the IDs are well-established and tested both with simulations and in the real machine. This study indicates that the new IDs probably will not be harmful to the beam dynamics and equilibrium parameters for SIRIUS.

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